PAPER AAS 95-326 .

RELAY SATELLITE ORBIT SELECTION CONSIDERATIONS FOR FUTURE ROBOTICS MISSIONS TO EXPLORE VENUS

Rolf Hastrup, Jet Propulsion Laboratory
California Institute of Technology

Robert McOmber, Kathryn Nelson, Stanford Telecommunications, Inc.

AAS/AIAA Astrodynamics Specialist Conference

HALIFAX, NOVA SCOTIA, CANADA 1447 AUGUST 1995

AAS Publications Office, P.O. Box 28130, San Diego, CA 92198

AAS 95-326

RELAY SATELLITE ORBIT SELECTION CONSIDERATIONS FOR FUTURE ROBOTICS MISSIONS TO EXPLORE VENUS

Rolf Hastrup*, Robert McOmber, Kathryn Nelson°**

The paper discusses orbit design trades relevant to use of a Venus orbiting relay satellite supporting a variety of potential Venus robotic mission types. The emphasis is on the impact of mission telecommunications requirements on selection of a relay satellite orbit and those characteristics of the relay satellite orbit that can benefit or hinder mission performance for the variety of potential Venus robotic missions now under consideration. The results reported in this paper are based on studies performed by the Jet Propulsion Laboratory and Stanford Telecommunications, Inc. under the sponsorship of NASA's Office of Space Communications.

INTRODUCTION

This paper is based on a portion of the studies that NASA's Office of Space Communications has berm sponsoring to understand the efficient and effective utilization of planetary data relay networks to increase the science mission return, while concurrently reducing associated operational life-cycle costs. The Jet Propulsion Laboratory has been serving as the study and contract manager for this effort, Stanford Telecommunications, Incorporated has been awarded a study contract to perform relay network technical analyses.

In recent years there has been a rebirth of interest in NASA'S long term mission of planetary exploration. Following the recent successful Magellan mission to Venus, there is increased interest in possible robotic missions to Venus. In particular, several concepts for robotic missions to obtain information relevant to the atmosphere and surface of Venus are now under consideration by NASA.

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* Task Manager, Mission Design Section, Jet Propulsion Laboratory, California Institute of Technology

** Member of the Technical Staff, Stanford Telecommunications, Inc.

° Communications Engineer/Analyst, Stanford Telecommunications, Inc.

For all of the potential missions currently under consideration, telecommunications is essential for returning gathered scientific data to Earth. With distances between Venus and Earth ranging between 0.3 and 1.7 AU, communications equipment supporting direct links between Venus and Earth can represent a significant mass, power, and cost burden for any mission element in the Venus region,

With the potential for multiple simultaneous elements at Venus, the costs associated with providing each element a separate communications capability with Earth can become excessive, One way to reduce this burden is to use a Venus orbiting relay satellite (VRS) to relay information between local Venus elements and Earth. With such a relay, individual mission elements need only have communications equipment supporting a link to and from the relay satellite -- at much lower mass, power, and cost than a system capable of communications directly to and from Earth. A relay satellite, by collecting data from local Venus elements and then later transmitting the data to Earth, offers the potential for supporting elements at Venus that are not directly visible from the Earth. Additionally, by consolidating all of the local Venus data into one high data rate transmission, the contact time for communications with Venus and the associated cost to the Deep Space Network (DSN) are reduced. For all of these reasons, the consideration of a Venus orbiting relay satellite providing communications support to multiple missions in the Venus region appear's appropriate at this time,

POTENTIAL VENUS MISSION ELEMENTS

A complete set of Venus missions and a corresponding set of mission elements have not been defined to date. However, a number of possible missions are currently under consideration, resulting in a variety of potential Venus mission elements, each having distinct mission needs. Due to the high cost of transportation to Venus, all mission elements have a common need to limit mass at Venus while still meeting mission science and data return requirements

The types of missions which are beii considered for Venus include

- **Atmospheric probes** for collecting data while descending through the atmosphere of Venus. These probes are not generally expected to survive impact and may have memory for the hypersonic portion of the descent (during which communications is impossible), but otherwise would perform real-time continuous transmission of data. A penetrator's lifetime is expected to be about one hour, the time from orbit to surface impact.
- **Landers** of several varieties for surface studies, Landers in successive missions are expected to have progressively longer lives with lifetimes up to a year or more potentially feasible, Multiple simultaneous landers, distributed over a range of latitudes and longitudes, are desirable for seismic data collection. Landers may come in a variety of sizes and capabilities. Larger, longer lived landers would be designed to collect large quantities of data and would need frequent contacts to transfer that data and receive commands. Smaller landers would have proportionally less capability/shorter lifetime,

- **Balloons** for surface sampling and atmospheric information gathering. These would ride the quickly moving Venusian atmosphere and could circumnavigate the planet in as little as four days. Descent to the surface and return to the upper atmosphere in an increasingly controlled manner is anticipated as the balloons and control systems evolve. Balloons are expected to communicate their data from the. top of the atmosphere.

All of these mission types are ones for which Earth communications could be enhanced by an orbiting relay satellite

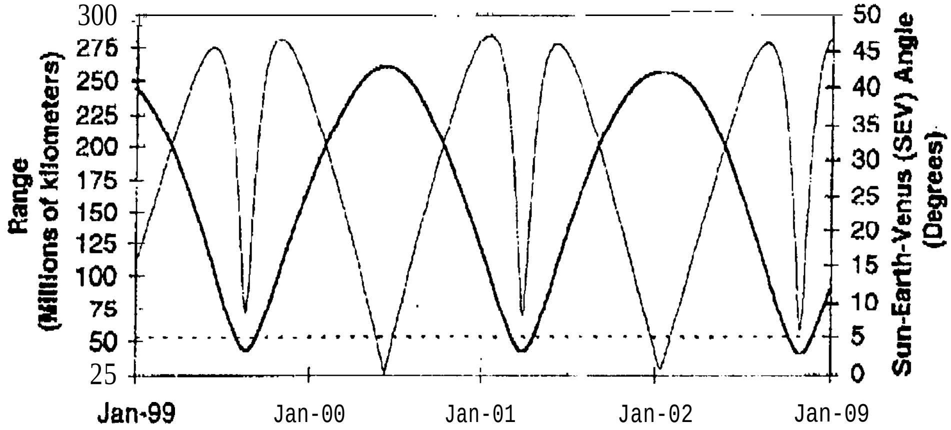
NEED FOR A VENUS-ORBITING RELAY SATELLITE (VRS)

As briefly mentioned above, a VRS can provide several advantages to the mission elements relative to direct Venus-Earth communications Of key importance is the relaxation of mass and power requirements for the local Venus mission element-s provided by communications via a VRS. Figure 1 shows both the variation of Venus-Earth distance over time and the angle between the centers of the Sun, Earth, and Venus (the SEV angle). The range between Earth and Venus can be as large as 2.54×10^8 km (1.7 AU) and, since received power on a communications link decreases as the square of range, this distance represents a substantial penalty to a Venus mission element when compared to communications with a VRS at a range of a few thousand kilometers. For example, a lander transmitting to a VRS at a range of 16,000 km could achieve a data rate of 6 kb/s using only a small hemispherical coverage antenna and 4 Watts of radio frequency (RF) power. To transmit at this data rate to Earth at maximum range would require a 1.5 m steerable dish antenna and an RF power level greater than 150 Watts. (These results assume operation at S-band and, for communications directly to Earth, use of a 34m Deep Space Network (DSN) antenna.) While landers having a short mission lifetime could conceivably be timed to arrive at Venus during periods of reduced Venus-Earth range, operation at times of minimum range is constrained by interference from the Sun when the SEV angle is small. The horizontal line of Figure 1 illustrates a boundary SEV angle of 5° -- solar interference is potentially possible when the SEV angle drops below this level.

The reduction in lander mass and power achievable through use of a VRS for communications is potentially a very significant cost savings. If only a single Venus lander is to be deployed, these savings may be offset by the cost of the VRS itself, but, if there are multiple Venus mission elements, a substantial overall reduction in mission costs may be possible.

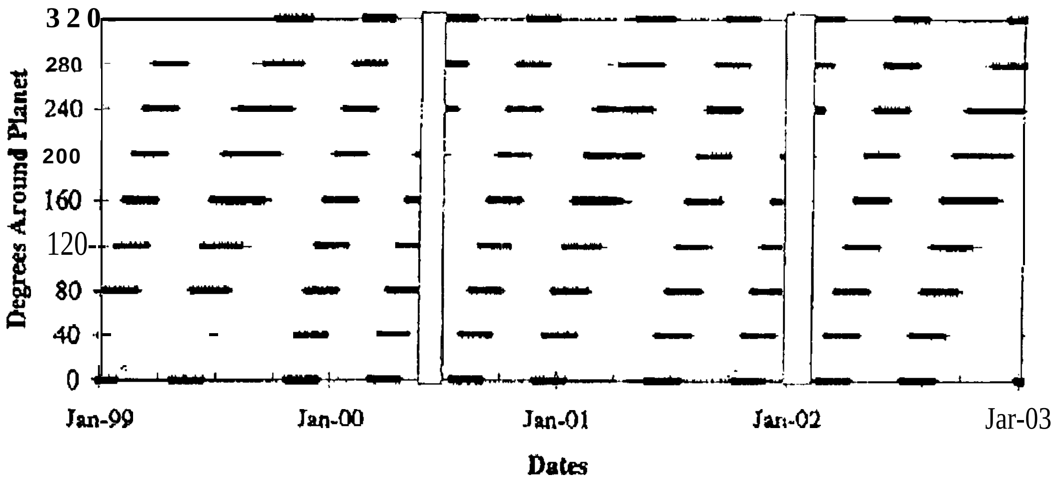
A second key benefit associated with use of a VRS for relaying data from Venus mission elements to Earth is the enhanced connectivity provided by the VRS. Due to the slow rotation rate of Venus (one rotation per 243 Earth days), even landers deployed near the equator of Venus are subject to lengthy communications outages to Earth as Venus rotates, For landers at high latitudes, direct visibility to Earth may not exist -- rendering communications impossible without the use of a VRS for data relay.

For example, Figure 2 illustrates contact times from selected points along the equatorial surface of Venus to the Earth over a period of several years. The figure illustrates periods of contact (horizontal lines) assuming minimum operational lander elevation angles of both 30° and 10°. The vertical bars indicate periods of potential solar interference corresponding to an SEV angle less than 5°. As illustrated, gaps in coverage of greater than 100 Earth days are possible even with a lander elevation mask of 10°. Figure 3 illustrates similar periods of direct-to-Earth connectivity for points on Venus at various latitudes along a single longitude line. Venus's equatorial plane has a relatively small inclination with respect to the ecliptic, thus, while sections of the equator see Earth regularly, higher latitudes have more restricted visibility and the poles lack visibility to Earth during the examined interval.



Note: Communication difficulties occur near superior conjunction with SEV angle below approximately 5°

Figure 1 Venus-Earth Range and Sun-Earth-Venus Angle over **Four-Earth Years**



Visibility from points with elevation masks of: 30 degrees
10 degrees

Figure 2 Direct-to-Earth Visibility from Points Around the Venus Equator for Four Earth Years

As described in the following sections, a properly designed VRS orbit can overcome many of these limitations and, in the case of missions to the poles of Venus, open exploration opportunities not otherwise available.

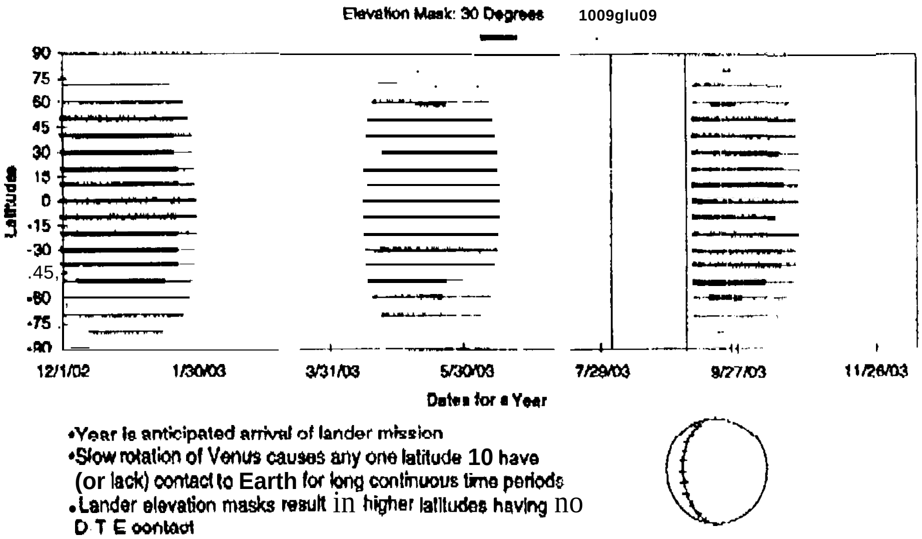


Figure 3 Continuous Direct-to-Earth Visibility Opportunities for Venus Lander Locations Along a Single Sample Latitude

KEY VRS ORBIT SELECTION TRADES

Given that one and perhaps two relay satellites might be located at Venus at any point in time, the chosen orbit(s) can be optimized to satisfy both the needs of the expected Venus mission elements and the unique requirements associated with VRS deployment and operations, Key factors examined in the VRS orbit evaluations of this paper are as follows:

> **VRS In Situ Coverage and Contact with Mission Elements.** Orbit characteristics should provide mission elements regular contact with the VRS to maximize data return and to provide frequent opportunities to monitor element status and intervene if problems arise.
>
> **Data Return from In Situ Elements.** It is important to provide adequate data return from mission elements while minimizing mass and power required at the surface of Venus. While the communicat ions implementation strongly impacts in situ data return to the VRS, the VRS orbit altitude and available contact time both also greatly impact the amount of data that can be returned.

Occultations of the VRS-Earth Link and Solar Eclipses. VRS operations can be significantly simplified by minimizing both occultations of the VRS-Earth link (by Venus) and the fre qency and duration of VRS solar eclipses. Communications through a VRS siould keep Venus-dedicated DSN time to a minimum. Since the DSN is shared among many users, occultations need to be limited to maximize the DSN flexibility in service to the VRS. Limiting solar eclipses simplifies in situ VRS operations by increasing the VRS'S time in sunlight for full power operations and reducing VRS battery requirements.

VRS Orbit Insertion AV Requirements. Like any element located at Venus, a VRS faces high interplanetary transportation costs. For this reason, selection of a VRS orbit should not only consider the communications/operations trades outlined above, but also the relative AV costs of the various orbit choices.

VRS IN SITU COVERAGE AND CONTACT WITH MISSION ELEMENTS

Single VRS

A single Venus relay satellite can only provide contact to a limited band of surface users. those some distance on either side of its ground trace, and, due to the slow rotation of Venus, coverage will be approximately unchanged for weeks at a time. The width and placement of the band. or swath, of surface coverage provided by a VRS is mbit dependent and also limited by the minimum usable lander-to-VRS elevation angle (or mask angle). Figure 4 depicts instantaneous contact provided by a single VRS at two different altitudes. Using the same ground elevation mask, higher altitude satellites have a larger coverage area, which, as the satellite orbits Venus, results in a wider swath of coverage. For even very high altitude satellites and users with large amounts of power, an equatorial satellite is prevented from seeing surface users near either pole. The coverage swath of a polar satellite with a 90° inclination, covers both poles, but only two sections of the equator are provided coverage each orbit.

Even over several Earth days, a single VRS cannot provide coverage of the entire surface of Venus; thus, the location of the landed elements effects the VRS orbit choice. For many of the candidate Venus surface missions, locations may be restricted to lower latitudes of Venus, with only limited surface missions and balloons reaching higher latitudes, For this reason, coverage evaluations have focused on orbits that assure daily coverage to all surface points within the mid-latitude regions of Venus while providing some (but not necessarily daily) coverage to the polar regions. Note that in the case of balloon missions, the rapidly varying longitude of the balloon can potentially prevent long periods without VRS contact as long as the VRS has some visibility to the latitude at which the balloon is operating. Also note that the balloons, riding near the top of the atmosphere, face fewer elevation restrictions than surface users, permitting contact with the VRS in situations where it might not otherwise be possible.

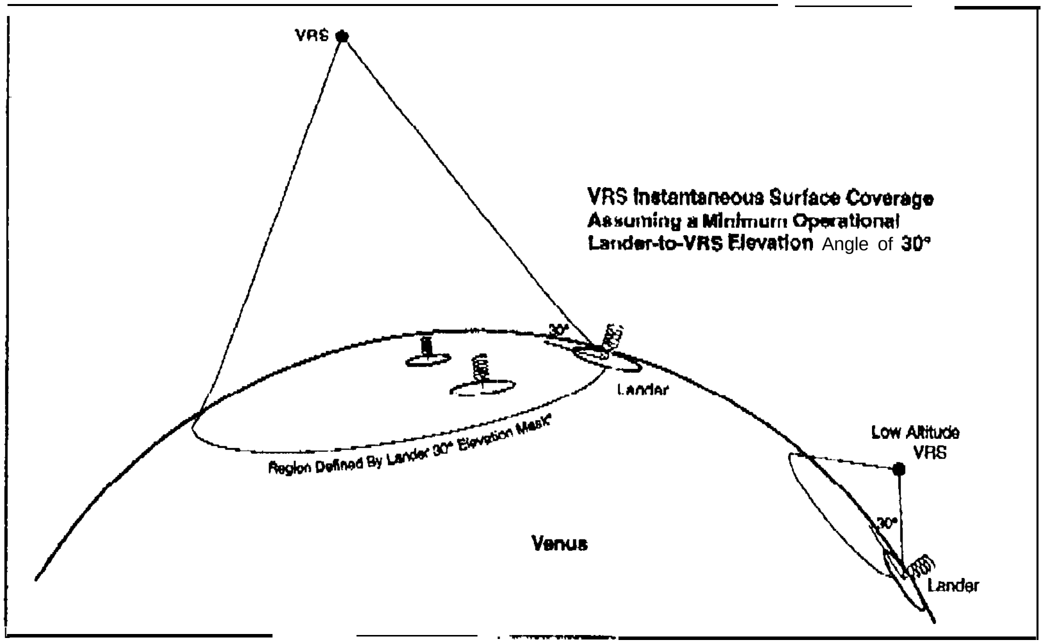


Figure 4 VRS Surface Coverage

Circular Orbits

Figure 5 defines in situ coverage provided by a variety of circular Venus orbits, emphasizing orbits that provide daily coverage to the equatorial regions of Venus. The dashed lines define combinations of VRS altitude and inclination that provide coverage (each Earth day) to all surface points on Venus within a swath of indicated angular extent about the equator of Venus. The solid lines define orbits that provide some coverage to either ±80° or ±90° latitude. For example, if a circular orbit with an altitude of 10,000 km is inclined, that inclination can go as high as -40° and the VRS can still provide service to a lander anywhere along the entire equator, as shown by the dashed equator demarcation line. Any circular orbit with a combination of altitude and inclination which plain it above and to the right of the 90° line will be able to see the poles. Relay satellites with the combination of characteristics located to the right and between the equatorial line and the pole line will be able to see both the entire equator and both poles, though there will still be holes in the coverage at middle latitudes.

Elliptical Orbits

An elliptical orbit's swath of coverage (using a constant lander elevation mask) varies in width as its altitude varies over an orbit, The width of the coverage at periapsis, when the satellite is closer to the surface, will be much narrower than the width of the swath at apoapsis. The velocity of an elliptical satellite also changes during the course of its orbit so that it travels more quickly over its periapsis and travels slowest at apoapsis. The small J2 perturbation term of Venus results in negligible regression of the line of nodes or rotation of the line of apsides for the elliptical orbits under consideration. However, the slow surface rotation will result in Venus lander locations moving relative to the VRS orbit. The resulting variations in lander contact time and communications range must be considered when examining an elliptical orbit.

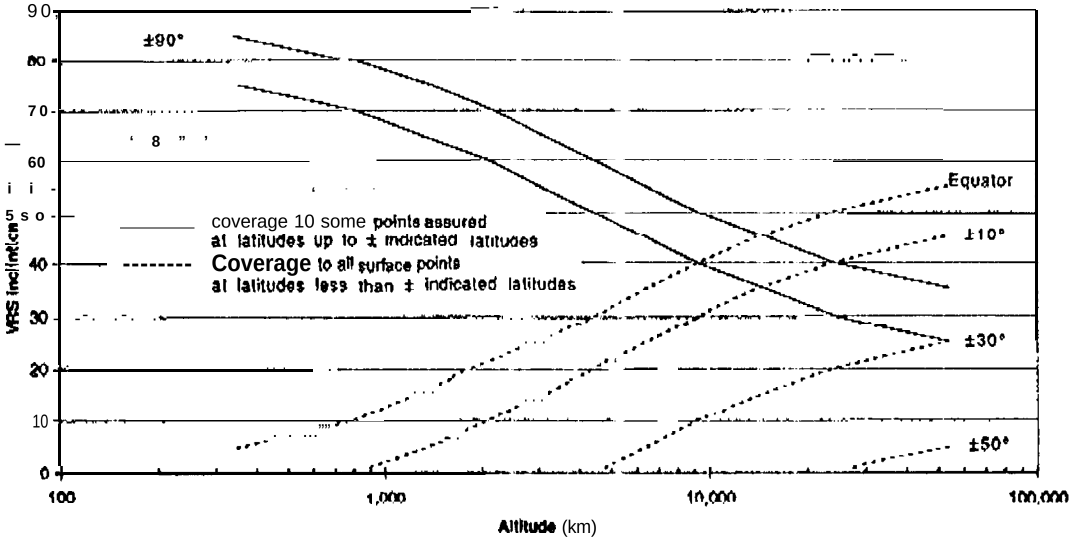


Figure 5 Venus **Surface Regions Provided Connectivity by Various Circular VRS Orbits**

Figure 6 shows the swath of contact for a highly elliptical orbit having a 12 hour period and 600 km periapsis altitude. The orbit is inclined 30° and has its line of apsides within the equatorial plane of Venus. Placing the line of apsides coincident with the line of nodes allows for complete equatorial coverage for landers with a 15° minimum elevation viewing restriction. Note that the amount of the surface provided coverage varies greatly between apoapsis and periapsis. Thus the eccentricity of the chosen orbit influences the range of potential lander locations that can be **provided communication service.**

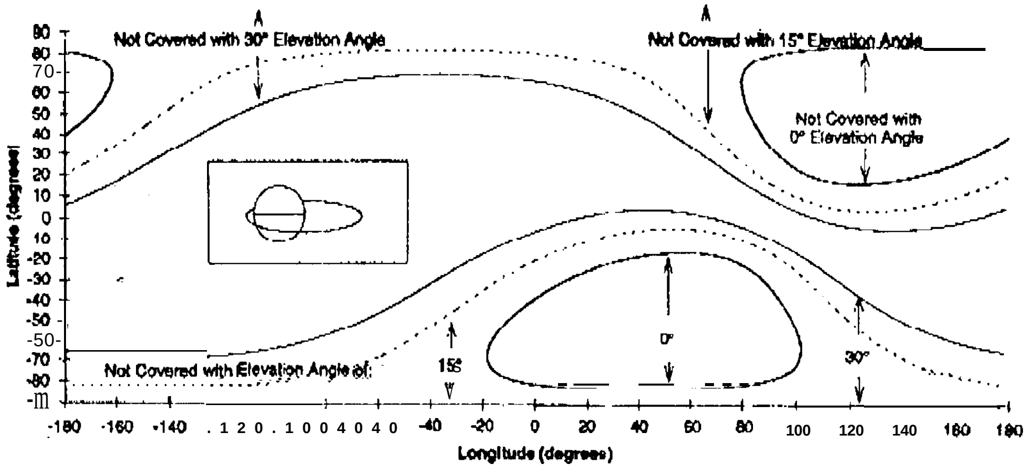


Figure 6 Surface Regions Provided Coverage by a 12 hr Elliptical VRS Orbit (h_p = 600 km) at Various Minimum Lander Elevation Angles

A sample of the amount of contact time available to points on the surface for a 12 hour, 600 km periapsis orbit, inclined **55 degrees, is depicted in Figure** 7. Here **the apoapsis is** over **zero** degrees longitude. Contact times range from O to 1100 minutes out of the 1440 minutes in 24 hours. Note the holes in coverage for the two opposing middle latitude **sections,**

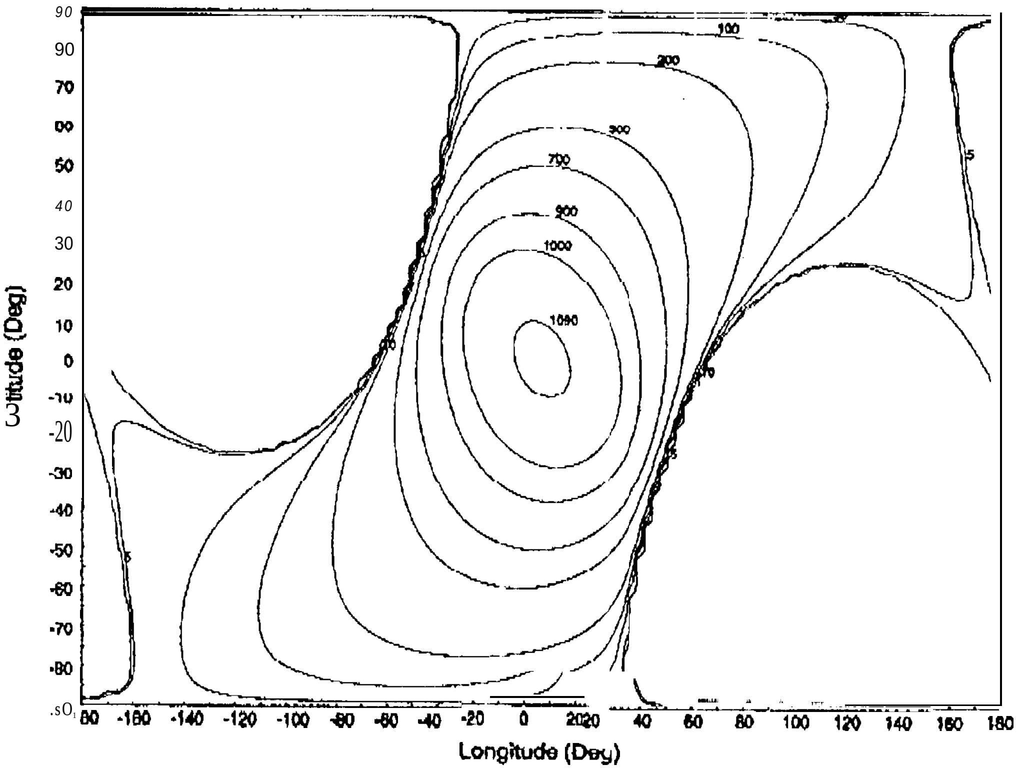


Figure 7 Lander-to-VRS Contact Time per 24 Hours vs Lander Location
Assuming Lander 30° Elevation Mask
VRS Orbit: 55” Inclined, 12 Hour Period, Periapsis Altitude = 600 km,
Apoapsis Altitude= 37,000 **km, Line of Apsides Parallel to Line of Nodes**
No Time Reserved for Contact with Earth

Elliptical orbits can be poor choices for long lived landers. As Venus revolves, landers will experience very large variations in VRS-provided coverage and may lose communications opportunities when nearly beneath VRS orbit periapsis. Such long lived landers may experience very short or missed communications opportunities for significant periods of time (e.g., several weeks or months). Short term landers or penetrators deployed under the current apoapsis could make good use of an elliptical orbiting VRS. Balloons, as independent flyers, could be well serviced by a VRS in a highly elliptical orbit which would remain relatively stationary for a portion of each orbit. The high wind speeds on Venus should carry the balloon around Venus and into contact with a **VRS,** on a less regular basis than a surface element, but with enough frequency to allow the VRS to serve as the balloon data relay to Earth.

Multiple VRSs

A solution to the holes in coverage provided by a single VRS is a pair of relay satellites. For example, two VRSS could provide global daily coverage to the *surface* of Venus with matching inclinations of approximately 45 and 135 degrees, altitudes of 14,200 km, and periods of 8.8 hours. Two similarly inclined, 12 hour elliptical orbits achieve global coverage with a periapsis of 7900 km. Using two VRSS means that two sections of the equator would receive coverage from both satellites.

Coverage Conclusions

Coverage considerations tend to drive the orbit choice towards high altitudes, thus increasing both *the* total portion of the planet that can receive daily contact and the lengths of contact to individual locations. If balloon element(s) are present, contact is easiest if at least a portion of the orbit has a high altitude, otherwise, the probability of the balloon being in the VRS field of view is reduced, Additionally, the regular contact which a VRS provides allows scientists to monitor a lander's performance and possible degradations.

DATA RETURN FROM IN SITU ELEMENTS

Returned data is a basic requirement of any interplanetary mission. The in situ data return, the amount of data received at the VRS for return to Earth, is a function of several parameters including: distance, power, frequency, and receive antenna size. Assuming that each major lander has large amounts of data and that all surface elements use the same frequency band, the amount of data that the VRS can collect is dependent upon how long it sees a particular element and the number of bits per second that the surface element is designed to send and the VRS is designed to receive.

A sample link budget for a 12 hour, circular orbit is shown in Table 2. It assumes the maximum range to a lander at the edge of a 30° ground elevation mask and includes VRS antenna pointing losses, S-band is the chosen frequency, as Venus atmospheric attenuation losses are higher at higher frequencies, resulting in lower data rates.

Table 2
SAMPLE LINK BUDGET FOR CIRCULAR ORBIT,
12 HOUR PERIOD

Frequency Band	S-band
Frequency	2.295 GHz
Lander Antenna Type	Hemi
Lander RF Power	4.0 W
Path Losses (Maximum Slant Range = 21300 km)	186.2 dB
Atmospheric Attenuation	1.01 dB
VRS Receive Antenna Type	1.5 m Dish
System Noise Temperature	614.9 K
Modulation	Suppressed Carrier BPSK
Coding	Convolutional
Bit Error Rate	10-6
Achievable Data Rate	3.5 kb/s
Margin + Losses	7.s dB

Similar link budget results were used to generate Figure 8 which examines in situ data **return** for a **range** of circular orbits. Here the lander and VRS parameters have been held fixed in the exhibit (fixed transmit power. frequency, antenna choice and size). The aggregate data return potential for each surface location is plotted. The decrease in the aggregate data return per location per day for higher altitude, longer period VRSS is a result of the increased communications range. Note that, while contact times are greater for higher altitude orbits, the return data rate achieved by a surface element decreases as the square of **communications range** (all **other factors** being freed) resulting in a net decrease in **data returned**.

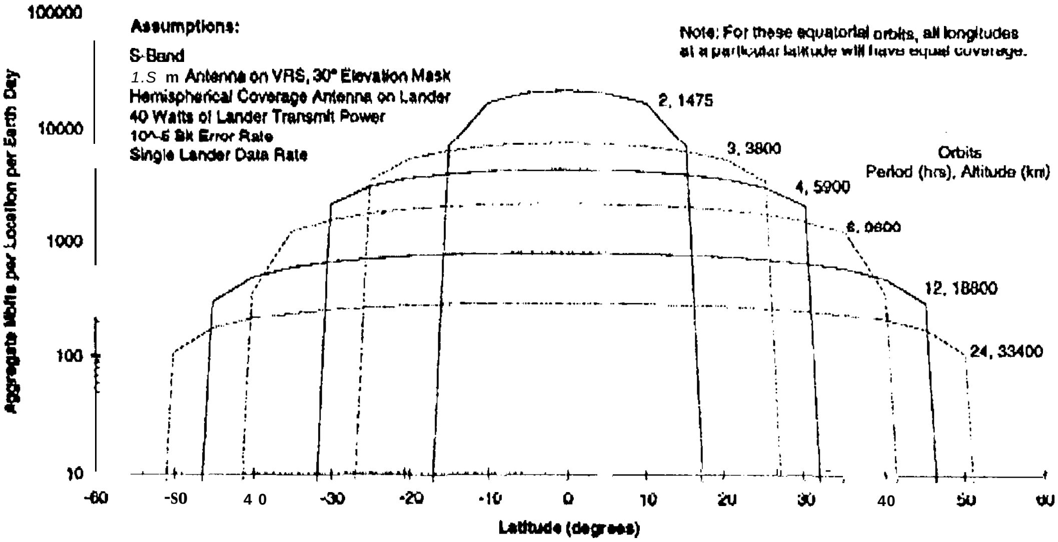


Figure 8 In Situ Return Data Quantity for Various Circular, Equatorial VRS Orbits and Lander Locations.

For highly elliptical VRS orbits, the situation is somewhat more complex, Due to the very large variations in surface-to-VRS range and contact times occurring during an elliptical orbit, rate adaptation schemes, adapting the data rate to an optimum value corresponding to local communications conditions, need to be used to maximize the data returned to the VRS. An elliptical VRS could take advantage of its extreme dwell time near apoapsis to contact Earth, This would allow for long Earth contacts without loss of local data.

Figure 9 illustrates aggregate data return from surface points to the VRS as a function of surface location over a one day period for an example elliptical VRS orbit. Using rate adaptation to permit the data rate to be raised as the range to the surface is reduced, permits significant data quantities to be returned to the VRS by points beneath the VRS periapsis despite their very short contact times (e.g., a few minutes].

Varying data rates is a good example of adding complexity to enhance data return. Encoding can be used by a lander to compress information so that fewer transmitted data bits are required, but this adds complexity to both the landers and the communications scheme, There is a theoretical limit to the amount of compression which can take place. Adding complexity to the communications packages of both the landers and the VRS, in order to enhance performance for elliptical orbits, needs to be weighed against the difficulty of circularizing the VRS orbit.

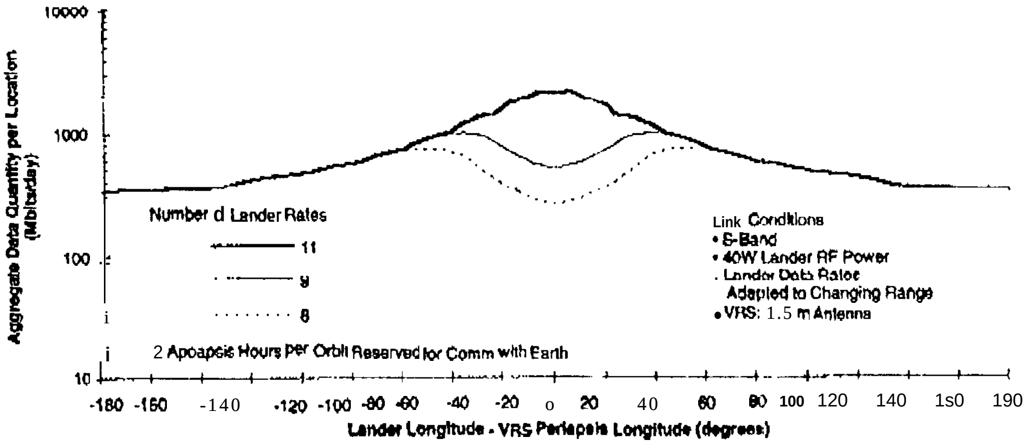


Figure 9 In Situ VRS Return Data Quantity per Day vs. Number of Lander Data Rates
VRS: Periapsis Altitude = 600 km, Period = 12 Hours, Inclination = 0°, Eccentricity = 0.73
Lander at 0° Latitude, 30° Elevation Mask

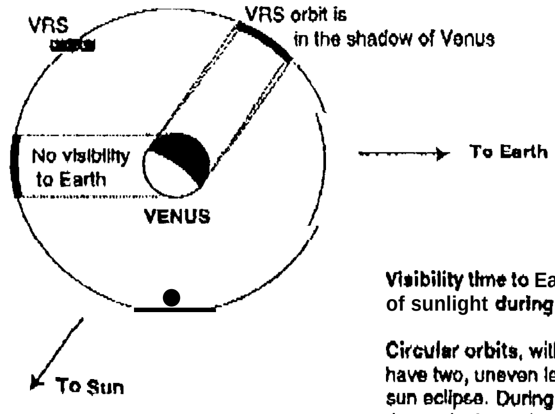
As has been illustrated, the amount of data that a VRS could return to Earth is highly orbit dependent. Limiting the lander's available transmit power, keeping the VRS receive antenna to a reasonable size, maximizing the data rate within the complexity that the mission budget will allow, and trading these parameters against the orbit choice becomes a multi-dimensional balancing act. It is highly dependent on future decisions concerning the number of landers at Venus at any onetime, their locations, and capabilities.

OCCULTATIONS OF THE VRS-EARTH LINK AND SOLAR ECLIPSES

Orbit selection for a solar powered VRS spacecraft design must be concerned with the coincidence of sunlight and contact times to Earth. Figure 10 illustrates the geometry involved in this consideration. Short, even length, Sun and Earth contact times will occur when Venus is between the Earth and the Sun.

Figure 11 provides example contact to Earth times, solar availability times and the union of the two intervals for two sample orbits, one low altitude circular and the other elliptical for 50 to 45 days before conjunction. As shown. the elliptical orbit, with its longer period, has longer continuous opportunities for Earth contact. The low altitude circular orbit has shorter gaps but might require more than one contact with Earth to transmit all of its stored data.

Figure 12 summarizes the contact times to Earth and solar availability for a range of mbit choices. For circular, equatorial satellites the VRS solar eclipse and Earth occultation times are reasonably constant. For an elliptical orbit, location of periapsis becomes a factor, but the contact times can be expected to match those of circular orbits having similarly long periods,



Visibility time to Earth is affected by the availability of sunlight during transmission times

Circular orbits, with their constant velocities, can have two, uneven length contacts, one on either side of the sun eclipse. During Sun - Earth - Venus conjunctions the contacts can become even or merge into one, but communications become difficult to impossible

Elliptical orbits, with their varying velocities, have a similar number of contacts per orbit but can suffer their maximum eclipse time when periapsis is on the Sun side of Venus.

Figure 10 VRS Sunlight Considerations

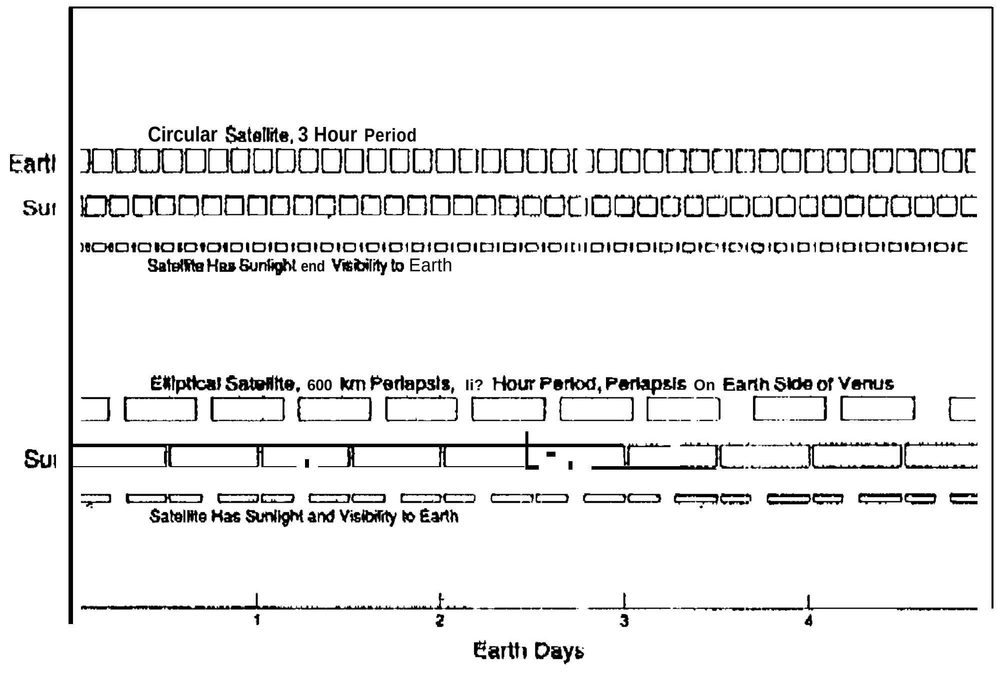


Figure 11 Venus Relay Satellite Visibilities to Earth and Sun
5 Day Plot Starts 50 Days Before Minimum Range to Earth
Both Orbits Have Zero Inclination
Circular Orbit: 3 Hour Period
Elliptical Orbit: 600 km Periapsis Altitude, 12 Hour Period

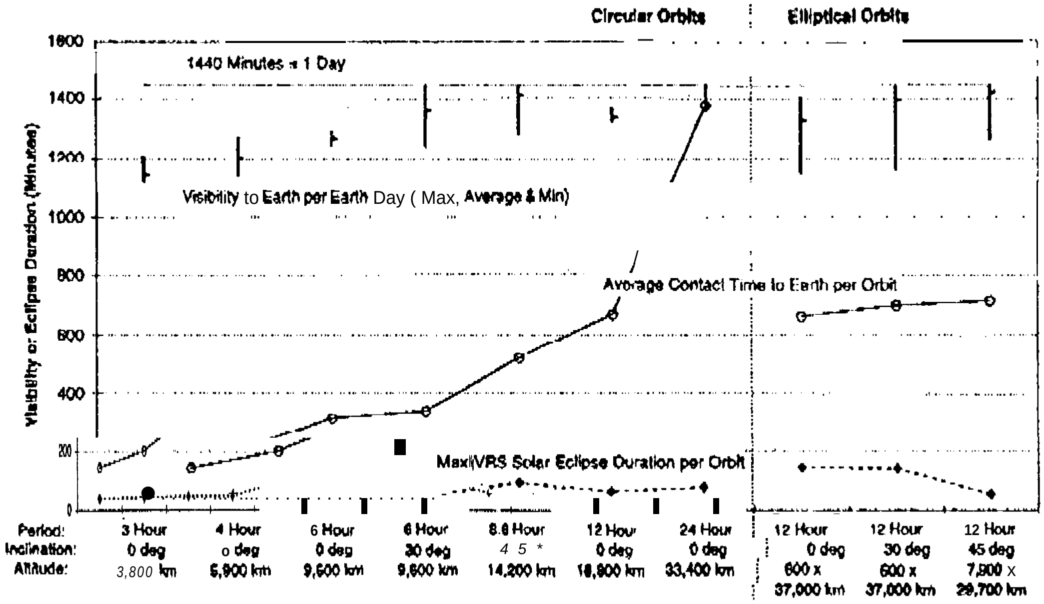


Figure 12 VRS Visibility to Earth and VRS Solar Eclipse Durations

ΔV TO ACHIEVE ORBIT

Geometric considerations and propellant equirements limit launch opportunities to discrete windows for interplanetary missions to Venus. In these time windows, propellant requirements to reach Venus orbit are within the vehicle propulsion capabilities available to the mission designers.

The change in velocity, the AV needed to go from an interplanetary trajectory to a particular orbit, is a significant factor influencing VRS deployment costs. For a given interplanetary trajectory, the higher the orbit insertion AV requirement, the more propellant needed at Venus, thus the higher the mass needed to be launched from Earth. Figure 13 considers two post-launch energy levels and examines the additional energy required to place a satellite into a range of possible orbits around Venus with varying eccentricity (e). It shows the relationship between the periapsis altitude above the surface of Venus and the period of the orbit for various values of orbit insertion AV and the energy available upon arrival at Venus. The more highly eccentric orbits with lower AV requirements are in the lower right portion of the figure, Choosing a lower AV orbit 'either sacrifices data return through lower data rates, or increases VRS and lander complexity.

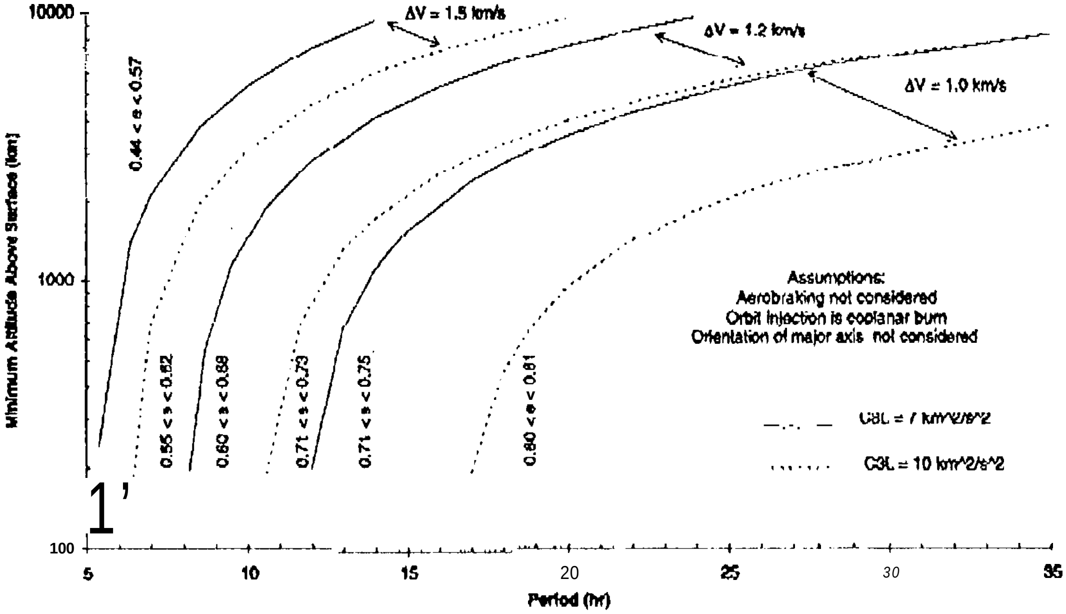


Figure 13 VRS Orbit Period Alternatives and Periapsis Altitude Effects on Orbit Insertion ΔV (Given C_3L of 7 or 10 km^2/s^2)

SUMMARY

A Venus relay satellite maybe an important element in future missions to Venus. It can reduce the communications burdens on each surface element and provide an amplified and consolidated communications link to the Deep Space Network. It enables continued communications with surface elements, beyond the limited window of direct visibility to Earth, and allows surface element locations to be chosen based on Venus features of interest and scientific gain rather than on which portion of Venus will see Earth for the time following arrival.

A VRS offers flexibility for surface elements to continue to produce data when they are out of direct visibility to the Earth. Flexibility is added to the choice of lander locations and errors are more recoverable. If a lander is improperly placed due to malfunctions, it may still be useful since the chance that it will see the VRS is high even if it would be out of direct contact with Earth for months at a time.

The selection of a VRS orbit has a large impact on overall mission performance for the potential Venus missions *now* under consideration. Final determination of orbit characteristics for the VRS will depend greatly on the set of Venus missions to be supported, their deployment locations at Venus, and the individual needs of each mission, The many important factors in orbit selection must be weighed. It will be necessary to **balance** the cost of circularizing an orbit against the inefficiency of a single data rate for an elliptical orbit or the cost and complex implementation of multiple data rates in both the **VRS and landers.**

ACKNOWLEDGMENTS

The authors wish to thank the following people for their contributions and insight,

Robert Cesarone, Assistant Program Manager, Deep Space Network Strategy Development, Jet Propulsion Laboratory, California Institute of Technology

Albert Miller, Assistant Associate Administrator (Plans), Office of Space Communications, NASA Headquarters

Kerry Nock, Member of Technical Staff, Jet propulsion Laboratory, California Institute of Technology

Aaron Weinberg, Group Vice-President for Communications Science Division, Systems Integration Group, Stanford Telecommunications, Inc.

Research described in this document was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration, and by Stanford Telecommunications, Inc. under Subcontract Nos. 958741 and 960229.

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